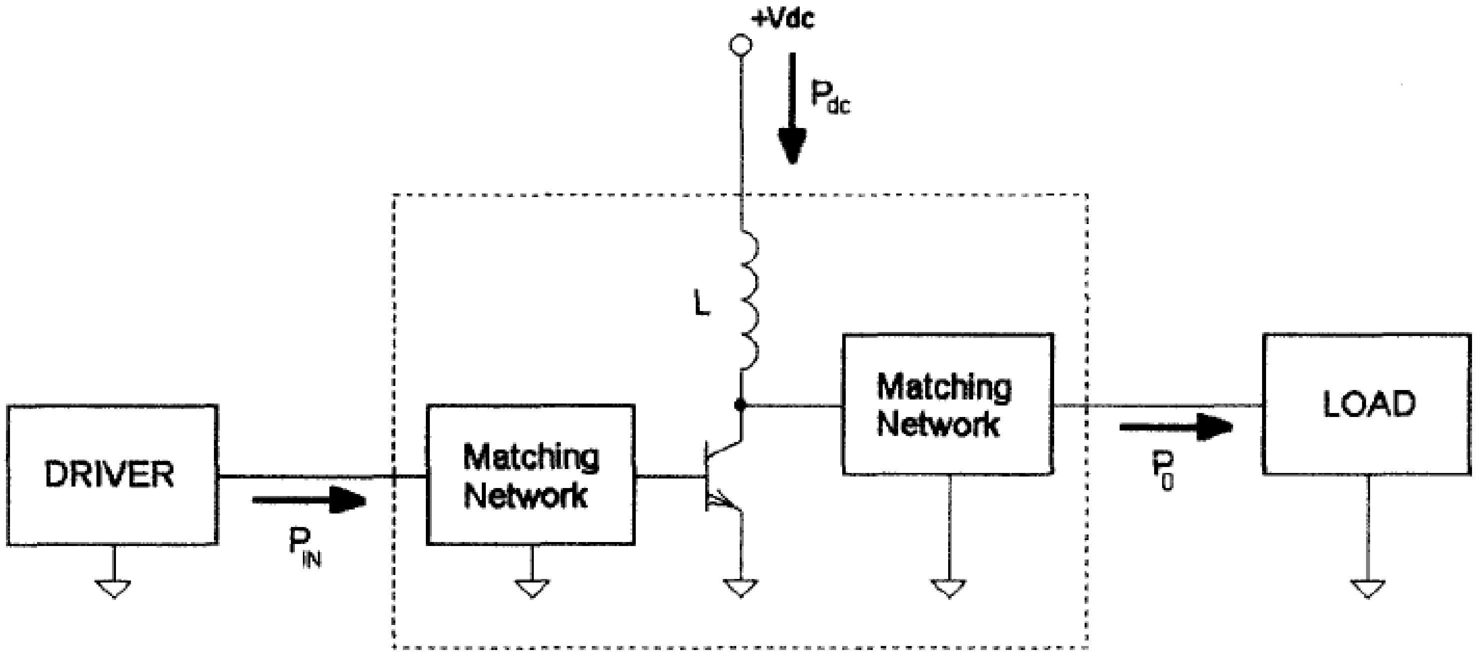
Chapter 2:

RF Power Amplifiers

Definitions (1)

- **Efficiency**: Efficiency is a crucial parameter for RF power amplifiers. It is important when the available input power is limited, such as in battery-powered portable or mobile equipment. It is also important for high-power equipment where the cost of the electric power over the lifetime of the equipment and the cost of the cooling systems can be significant compared to the purchase price of the equipment.



Definitions (2)

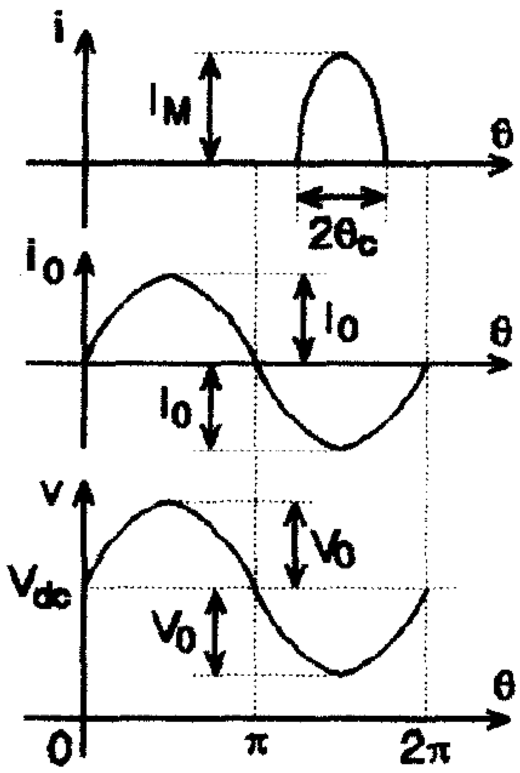
Collector efficiency: Collector efficiency is a term more appropriate for amplifiers using bipolar transistors (BJTs), although it is often used for any RF power amplifiers. Some authors prefer to use **plate efficiency** for amplifiers using vacuum tubes or **drain efficiency** for amplifiers using MOSFETs or, simply refer to it as **efficiency**. Collector efficiency is defined as

$$\eta = \frac{P_0}{P_{dc}}$$

where P_0 is the RF output power (dissipated into the load) and $P_{dc} = V_{dc} I_{dc}$ is the input power supplied by the dc supply to the collector (or drain /plate) circuit of the power amplifier. P_0 usually includes both the RF fundamental power and the harmonics power. In many applications, harmonic suppression filters are included in the output-matching network. Because the harmonic power is negligible, the RF fundamental power is a very good approximation for P_0.

Class C RF Power Amplifier (1)

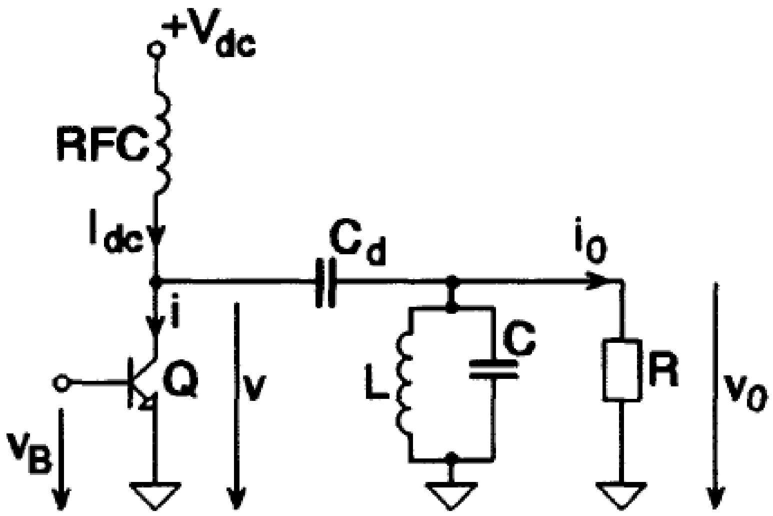
- **<u>Conductance angle</u>**: The portion of the RF cycle the device spends in its active region is the **conduction angle** and is denoted by $2\theta_C$. Based on the conduction angle, the amplifiers are generally classified as:



- **Class A amplifiers**, if $2\theta_C = 360°$. The active device is in its active region during the entire RF cycle.
- **Class AB amplifiers**, if $180° < 2\theta_C < 360°$.
- **Class B amplifiers**, if $2\theta_C = 180°$.
- **Class C amplifiers**, if $2\theta_C < 180°$.

Class C RF Power Amplifier (2)

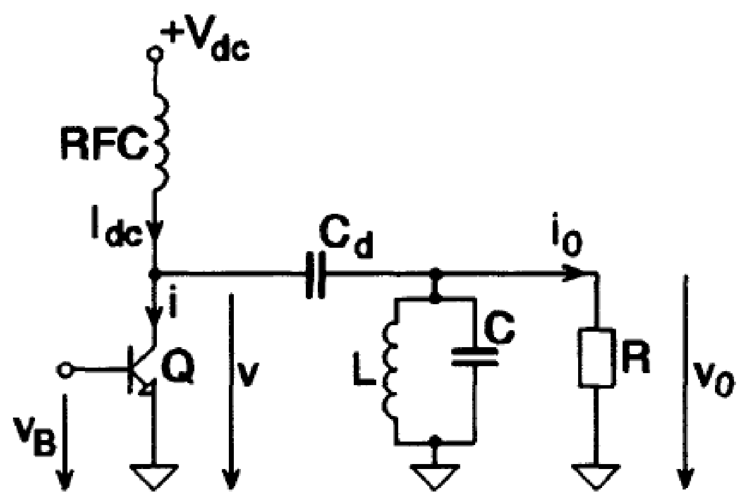
❑ **<u>Basic circuit of single-ended class A, AB, B, or C amplifier</u>**:



This is a single-ended circuit, and the transistor operates in the common emitter (CE) configuration (common-base configurations are also possible). Variations among practical circuits operating in **different classes may occur in the base-bias or drive circuits**. The collector circuit includes an RF choke (RFC) that provides a DC input current, I_{dc}, a DC blocking capacitor, C_d (short-circuit at the operating frequency and its harmonics), the load resistor, R, and a parallel resonant LC circuit tuned to the operating frequency ω_0.

Class C RF Power Amplifier (3)

The DC component of the collector current $i(\theta)$ flows through the RFC and then through the DC-power supply. The variable component of $i(\theta)$ flows through DC-blocking capacitor C_d and through the parallel RLC tuned circuit. The tuned circuit provides a zero impedance path to ground for the harmonic currents contained in $i(\theta)$ and only the **fundamental component** of $i(\theta)$ flows through the load resistance. As a result, the **output voltage** is a **sinusoidal waveform**. This requires the use of a parallel resonant circuit (or an equivalent band-or low-pass filter).



Class C RF Power Amplifier (4)

The collector current is a periodical waveform described by

$$i(\theta) = \begin{cases} \dfrac{I_M(\cos\theta - \cos\theta_c)}{1-\cos\theta_c} & -\theta_c + 2k\pi \le \theta \le \theta_c + 2k\pi \quad k \in Z \\ 0 \quad \text{otherwise} \end{cases}$$

Its Fourier analysis results:

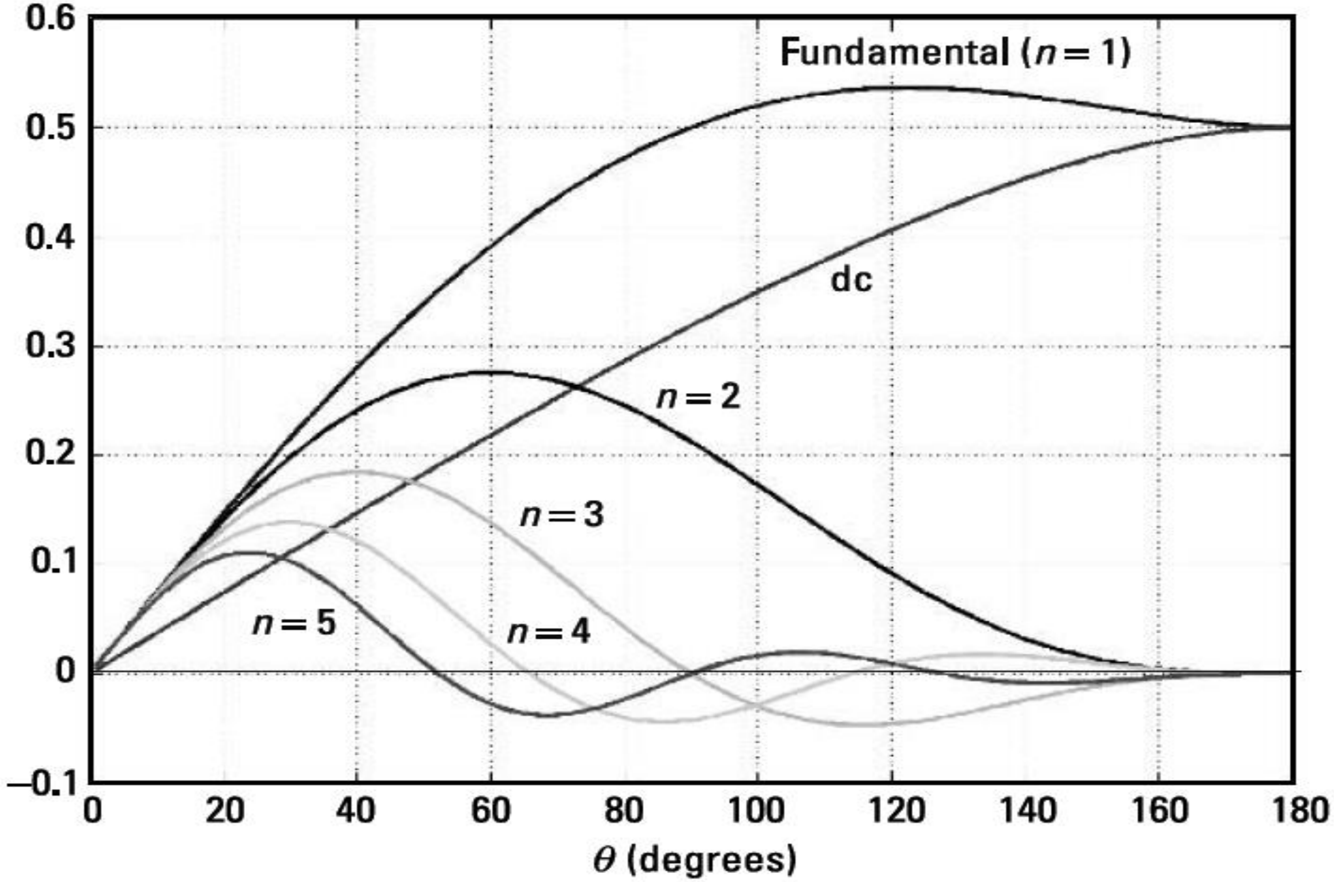
$$i(\theta) = I_M \sum_{n=0}^{\infty} \alpha_n(\theta_c)\cos n\theta$$

where

$$\alpha_0(\theta_c) = \frac{\sin\theta_c - \theta_c\cos\theta_c}{\pi(1-\cos\theta_c)} \qquad \alpha_1(\theta_c) = \frac{\theta_c - \sin\theta_c\cos\theta_c}{\pi(1-\cos\theta_c)}$$

$$\alpha_n(\theta_c) = \frac{\dfrac{\sin(n-1)\theta_c}{n-1} - \dfrac{\sin(n+1)\theta_c}{n+1}}{n\pi(1-\cos\theta_c)} \qquad n = 2, 3, \ldots$$

Class C RF Power Amplifier (5)



Fourier series coefficients α_n versus the conduction angle (θ_c)

Class C RF Power Amplifier (6)

Due to the ideal tuned circuit, the output current (flowing through the load resistance *R*) is sinusoidal and its amplitude is given by

$$I_0 = I_M \alpha_1(\theta_c)$$

As a result, the output voltage is also sinusoidal, with the amplitude $V_0 = RI_0$. The collector voltage is

$$v(\theta) = V_{dc} + V_0 \cos\theta = V_{dc} + RI_M \alpha_1(\theta_c) \cos\theta$$

The DC input power P_{dc} and the collector efficiency η are

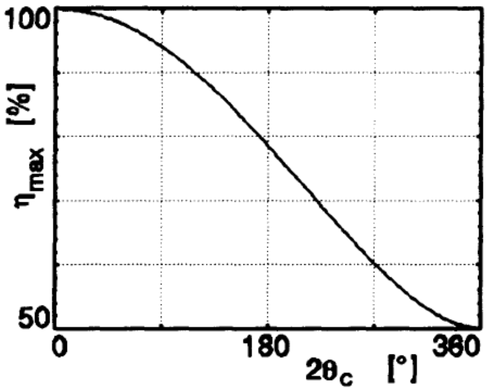
$$P_{dc} = V_{dc} I_{dc} = V_{dc} I_M \alpha_0(\theta_c)$$

$$\eta = \frac{P_0}{P_{dc}} = \frac{V_0^2}{2RV_{dc} I_M \alpha_0(\theta_c)} = \frac{V_0}{V_{dc}} \frac{\alpha_1(\theta_c)}{2\alpha_0(\theta_c)} =$$
$$= \frac{V_0}{V_{dc}} \frac{\theta_c - \sin\theta_c \cos\theta_c}{2(\sin\theta_c - \theta_c \cos\theta_c)}$$

Class C RF Power Amplifier (7)

The maximum theoretical collector efficiency (obtained for $V_0 = V_{dc}$) varies with the conduction angle as

$$\eta_{max} = \frac{\theta_c - \sin\theta_c \cos\theta_c}{2(\sin\theta_c - \theta_c \cos\theta_c)}$$



If $V_0 = V_{dc}$, the peak collector voltage is $v_{max} = 2\,V_{dc}$ and the peak collector current is given by

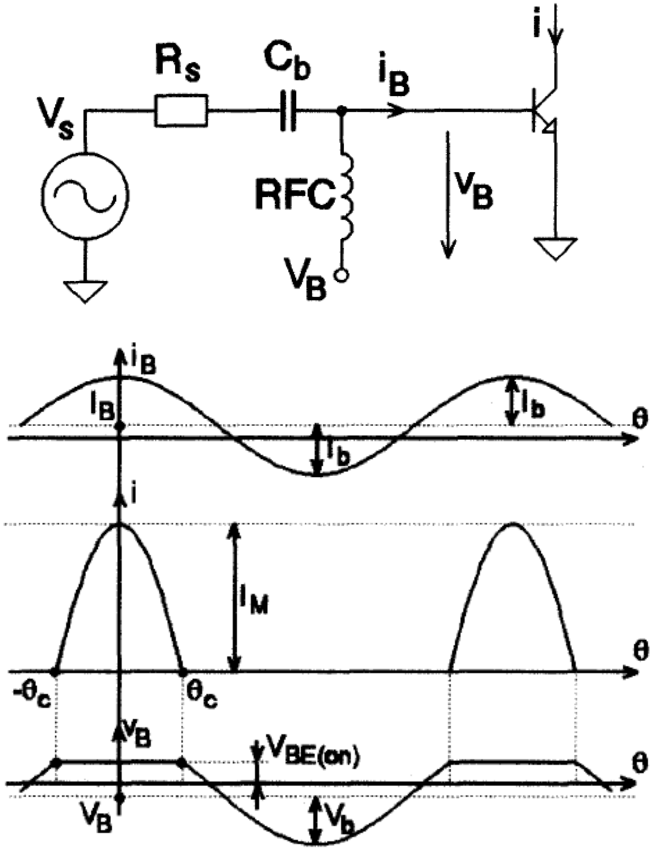
$$i_{max} = i_M = \frac{V_{dc}}{R\alpha_1(\theta_c)}$$

The output power P_0 is

$$P_0 = \frac{V_0^2}{2R} = \frac{V_{dc}^2}{2R}$$

Class C RF Power Amplifier (8)

- **DC bias**: The conduction angle in a Class C amplifier is controlled by a DC-bias voltage V_B applied to the base, and an amplitude V_b of the signal across the base-emitter junction.



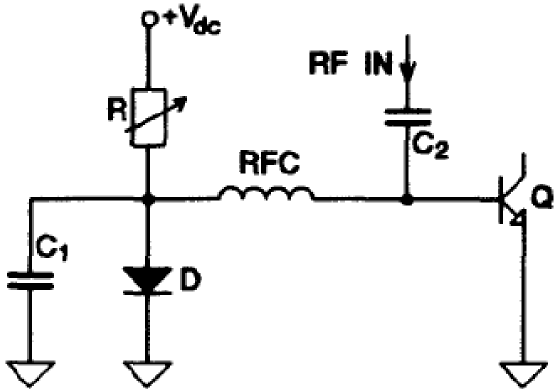
For $-\theta_c < \theta < \theta_c$, the transistor is in its active region. Consequently, the voltage across its base-emitter junction is $V_{BE(on)} \approx 0.7$ and

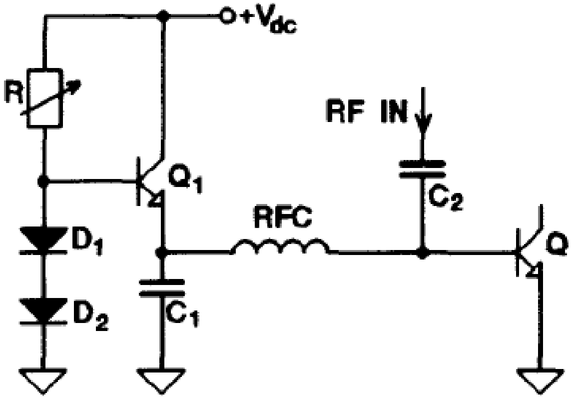
$$V_{BE(on)} = v_B(\theta_c) = V_B + V_b \cos\theta_c$$

This equation allows calculation of the required bias voltage, V_B, in the base circuit.

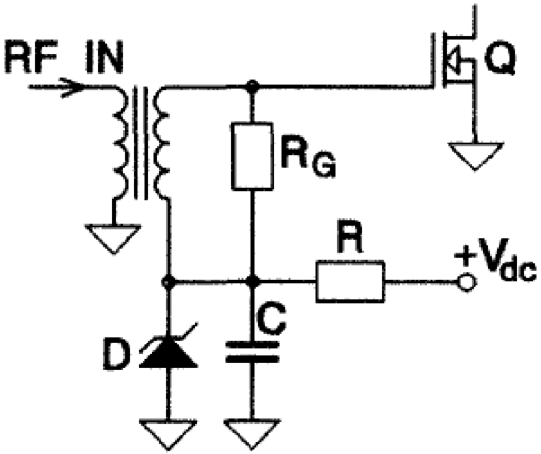
Class C RF Power Amplifier (9)

Simple bias circuits for BJTs





Simple bias circuits for MOSFETs



Class C RF Power Amplifier (10)

- **<u>Practical considerations</u>:** The effects of V_{sat} on the performance of Class C amplifiers are determined as

$$P_{0,max} = \frac{(V_{dc} - V_{sat})^2}{2R} \qquad \eta_{max} = \left(1 - \frac{V_{sat}}{V_{dc}}\right) \frac{\theta_c - \sin\theta_c \cos\theta_c}{2(\sin\theta_c - \theta_c \cos\theta_c)}$$

$$C_P = \frac{\alpha_1(\theta_c)}{2} \frac{V_{dc} - V_{sat}}{2V_{dc} - V_{sat}}$$

Class C Frequency Multipliers (1)

- Frequency multipliers are often used to multiply the frequency of the master oscillator or to increase the modulation index in the case of phase or frequency modulation.

  The Class C frequency multiplier has the **same schematic** as the Class C power amplifier and **operates in much the same way**. The only difference is that the collector **resonant circuit is tuned to the desired harmonic**, suppressing all other harmonics.

  Assuming that the parallel LC output circuit is ideal, tuned to the *n*th harmonic, a sinusoidal output voltage is obtained:

$$v_0(\theta) = V_0 \cos\theta = RI_M\alpha_n(\theta_c)\cos\theta$$

  The output power is given by

$$P_0 = \frac{V_0^2}{2R} = \frac{1}{2}RI_M^2\alpha_n^2(\theta_c)$$

Class C Frequency Multipliers (2)

The DC power is

$$P_{dc} = V_{dc} I_{dc} = V_{dc} I_M \alpha_0(\theta_c)$$

The collector efficiency is

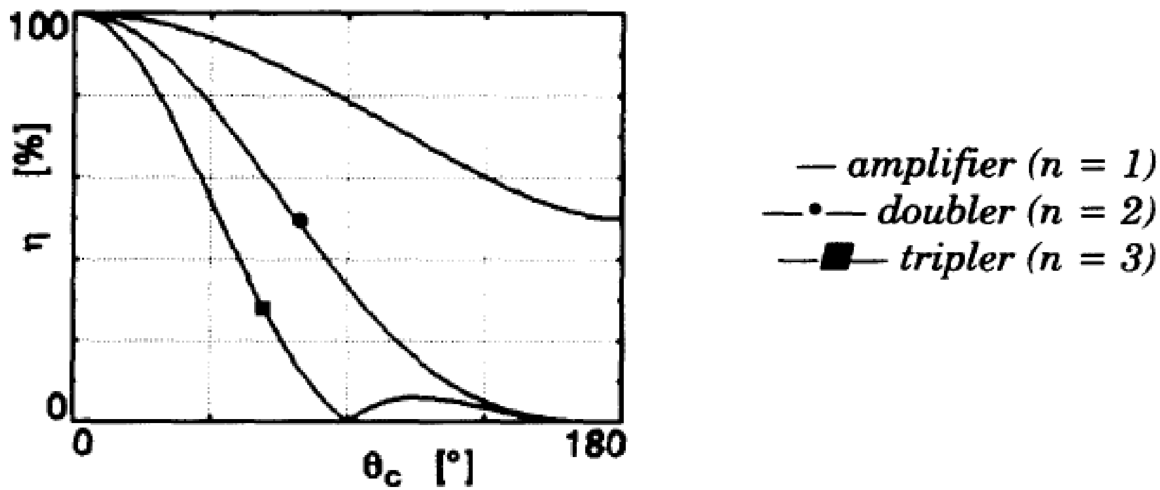
$$\eta = \frac{P_0}{P_{dc}} = \frac{V_0}{V_{dc}} \frac{|\alpha_n(\theta_c)|}{2\alpha_0(\theta_c)}$$

The collector efficiency is highest if $V_0 = V_{dc}$

$$\eta_{max} = \frac{|\alpha_n(\theta_c)|}{2\alpha_0(\theta_c)}$$

Class C Frequency Multipliers (3)

- The variation of the maximum collector efficiency η_{max} with the conduction angle θ_C, for a Class C amplifier (n = 1), a doubler (n = 2), and a tripler (n = 3), is shown



Note that the collector efficiency decreases as the multiplying order n increases. Also note that a Class B circuit (θ_C = 90°) cannot be used as a frequency tripler, because a half-wave sinusoidal waveform does not contain the third harmonic

Class C Frequency Multipliers (4)

- Optimum performance of frequency multipliers is obtained for

  a. frequency doubler: $\theta_C = 60°$, $\eta_{max} = 63.23\%$
  b. frequency tripler: $\theta_C = 39.86°$, $\eta_{max} = 63.01\%$

- As **multiplication factor *n*** **<u>increases</u>**, the **output power** (and also the **power gain** of the stage), the **collector efficiency**, and the **power output capability** **<u>decrease</u>**. On the other hand, if n increases, it becomes more difficult to filter out adjacent harmonics n - 1 and n + 1 because they lie closer to the desired harmonic, and the relative bandwidth becomes narrower. As a result, Class C frequency multipliers are not recommended for use at high power levels or for a multiplication factor exceeding $n = 3$.

Class D RF Power Amplifiers (1)

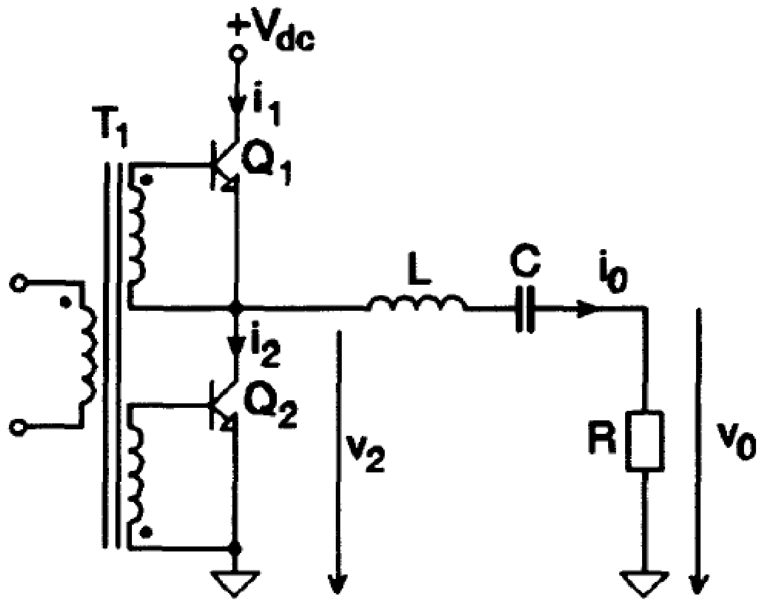
- Class D amplifier is a **switching-mode amplifier** that uses **two active devices** driven in a way that they are **alternately switched ON** and **OFF**.

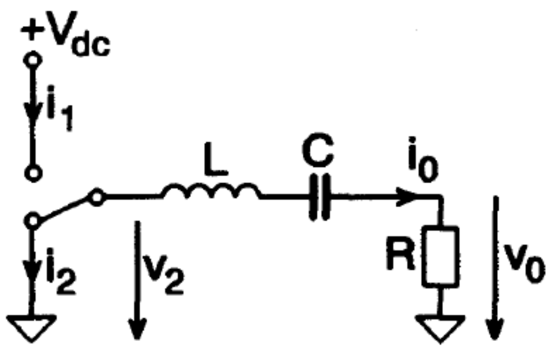
  The active devices form a two-pole switch that defines either a rectangular voltage or rectangular current waveform at the input of a load circuit. The load circuit contains a band- or low-pass filter that removes the harmonics of the rectangular waveform and results in a sinusoidal output.

  The load circuit can be a series or parallel resonant circuit tuned to the switching frequency. In practical applications, this circuit can be replaced by narrowband pi or T-matching circuits, or by band- or low-pass filters (in wideband amplifiers).

Class D RF Power Amplifiers (2)

- **<u>Complementary Voltage Switching</u>** <u>(CVS)</u> **<u>Circuit</u>**





Input transformer T_1 applies the drive signal to the bases of Q_1 and Q_2 in opposite polarities. If the drive is sufficient for the transistors to act as switches, Q_1 and Q_2 switch alternately between cut-off (OFF state) and saturation (ON state). The transistor pair forms a two-pole switch that connects the series-tuned circuit alternately to ground and V_{dc}.

Class D RF Power Amplifiers (3)

The analysis below is based on the following assumptions:

- The series resonant circuit, tuned to the switching frequency, *f*, is ideal, resulting in a sinusoidal load current. The CVS circuit requires a **series-tuned circuit** or an equivalent (that imposes a sinusoidal current), such as a **T-network**. A parallel-tuned circuit (or an equivalent, such as a pi-network) cannot be used in the CVS circuit.

- The active devices act as ideal switches: zero saturation voltage, zero saturation resistance, and infinite OFF resistance. The switching action is instantaneous and lossless.

- The active devices have null output capacitance.

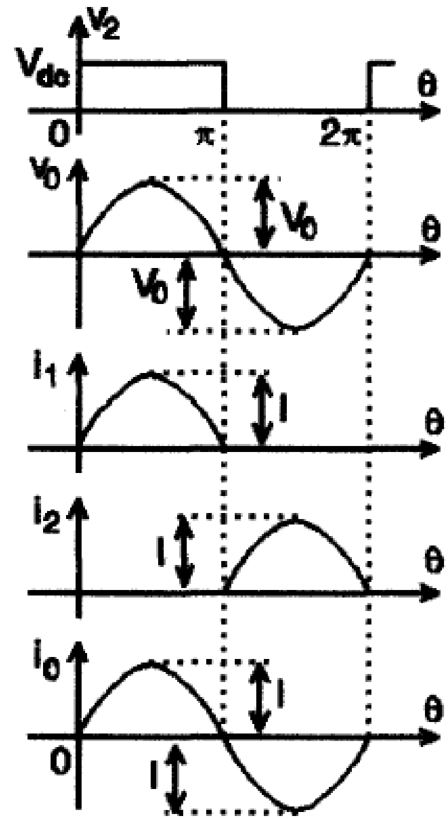
- All components are ideal. (The possible parasitic resistances of *L* and *C* can be included in the load resistance *R;* the possible parasitic reactance of the load can be included in either *L* or *C*).

Class D RF Power Amplifiers (4)

Assuming a 50 percent duty cycle (that is, 180 degrees of saturation and 180 degrees of cut off for each transistor), voltage $v_2(\theta)$ applied to the output circuit is a periodical square wave:

$$v_2(\theta) = \begin{cases} V_{dc}\,, & 0 \le \theta \le \pi \\ 0\,, & \pi \le \theta \le 2\pi \end{cases}$$

where $\theta = \omega t = 2\pi f t$.



Decomposing $v_2(\theta)$ into a Fourier series yields:

$$v_2(\theta) = V_{dc}\left(\frac{1}{2} + \frac{2}{\pi}\sum_{n=1}^{\infty}\frac{\sin(2n-1)\theta}{2n-1}\right)$$

Class D RF Power Amplifiers (5)

Because the series-tuned circuit is ideal, the output current and output voltage are sinusoidals:

$$i_0(\theta) = I\sin\theta = \frac{2}{\pi}\frac{V_{dc}}{R}\sin\theta$$

$$v_0(\theta) = V_0\sin\theta = \frac{2}{\pi}V_{dc}\sin\theta$$

At one moment, the sinusoidal output current flows through either Q_1 or Q_2, depending on which device is ON. As a result, collector currents $i_1(\theta)$ and $i_2(\theta)$ are half sinusoid with the amplitude:

$$I = \frac{2}{\pi}\frac{V_{dc}}{R}$$

The output power (dissipated in the load resistance R) is given by

$$P_0 = \frac{I^2}{2}R = \frac{2}{\pi^2}\frac{V_{dc}^2}{R} \approx 0.2026\frac{V_{dc}^2}{R}$$

Class D RF Power Amplifiers (6)

The DC input current is the average value of $i_1(\theta)$:

$$I_{dc} = \overline{i_1(\theta)} = \frac{1}{2\pi}\int_0^{2\pi} i_1(\theta)\,d\theta = \frac{I}{\pi} = \frac{2}{\pi^2}\frac{V_{dc}}{R}$$

The DC input power is given by

$$P_{dc} = V_{dc}I_{dc} = \frac{2}{\pi^2}\frac{V_{dc}^2}{R} = P_0$$

and the collector efficiency (for the idealized operation) is **100 percent**:

$$\eta = \frac{P_0}{P_{dc}} = 1$$